Final Report for Period: 07/2008 - 06/2009 **Submitted on:** 08/25/2009

Principal Investigator: Peng, Zhigang . **Award ID:** 0710959

Organization: GA Tech Res Corp - GIT

Submitted By:

Peng, Zhigang - Principal Investigator

Title:

Collaborative Research: Waveform Analysis of Repeating Earthquakes - Implications for Fault Damage and Healing Processes

Project Participants

Senior Personnel

Name: Peng, Zhigang

Worked for more than 160 Hours: Yes

Contribution to Project:

Name: Assamaki, Dominic

Worked for more than 160 Hours: No

Contribution to Project:

Dominic Assamaki from CEE in GT has participated in the project on detecting temporal changes in site response in Japan.

Post-doc

Graduate Student

Name: Zhao, Peng

Worked for more than 160 Hours: Yes

Contribution to Project:

Participated in identifying repeating earthquakes and extracting temporal changes from waveform analysis of repeating earthquakes.
Supported by both Teaching Assistantship and Research Assistantship from this grant.

Name: Wu, Chunquan

Worked for more than 160 Hours: Yes

Contribution to Project:

Participated in quantifying rapid temporal changes in fault zone site response based on spectral ratio analysis. Supported by both Teaching Assistantship and Research Assistantship from this grant.

Name: Chao, Kevin

Worked for more than 160 Hours: Yes

Contribution to Project:

Participated in quantifying temporal changes in seismic velocity and shear wave anisotropy from analysis of similar earthquakes in Taiwan. Supported by both Teaching Assistantship and Research Assistantship from this grant.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

Professor Yehuda Ben-Zion at University of Southern California worked with graduate student Chunquan Wu on identifying rapid temporal changes in fault zone site response based on a spectral ratio method.

Activities and Findings

Research and Education Activities:

The main goal of this project is to quantify the damage and healing processes in major fault zones that are recently ruptured in moderate to large earthquakes using waveform analysis of repeating earthquakes. We have conducted several research activities focusing on temporal changes inside active fault zones and near-surface properties associated with major earthquakes in California, Turkey, Taiwan and Japan. We have developed a simple technique to identify repeating earthquakes based on relocated earthquake catalogs and waveform similaries (Zhao and Peng, 2008, 2009), and systematically studied the damage and healing processes in the rupture zone of the 1984 M6.2 Morgan Hill earthquake along the Calaveras fault based on waveform analysis of repeating earthquakes (Zhao and Peng, 2009). We have examined temporal changes in the shallow near surface layers and deep fault zones based on systematic analysis of the UPSAR data before and after the 2004 Parkfield earthquake along the Parkfield section of the San Andreas fault. We have studied the temporal changes in seismic velocity and shear-wave anisotropy in the top 200 m before, during and after the 1999, M6.4, Chia-Yi, Taiwan, earthquake based on waveform analysis of similar earthquakes (Chao and Peng, 2009). Finally, we have quantified temporal changes and nonlinearity of fault zone site response along the Karadere-Duzce branch of the north Anatolian fault during the 1999 Mw7.4 Izmit and Mw7.1 Duzce, Turkey, earthquake sequences (Wu et al., 2009a), and temporal changes in the site response associated with the 2004 Mid-Niigata earthquake in Japan.

The project so far has led to five publications (two published, three accepted) plus two in preparation. The project supported three graduate students (Chao, Wu, Zhao), and the publications formed the major component of the thesis work of students Wu and Zhao. One faculty (Toteva) and two undergraduate students (Gerasimenko, Bagchi) from Randolph College have been involved in the research.

Findings:

Based on waveform analysis of more than 300 sets of repeating earthquakes along the Calaveras fault, Zhao and Peng (2009) found that the largest temporal changes are observed at station CCO that is the closest to the rupture zone of the 1984 M6.2 Morgan Hill mainshock. The time delays at this station are larger for clusters in the top 6 km, and decrease systematically at larger depth. In comparison, the time delays observed at other 5 stations are much smaller, and do not show clear relationship with hypocentral depth. We suggest that the temporal changes at these 5 stations mostly occur in the top few hundred meters of the near-surface layers, while the temporal changes at station CCO is likely associated with the damage zone around the Calaveras fault that is well developed in the top few kms of the upper crust. Our results are consistent with the inference of a widespread damage and nonlinearity in the near-surface layers associated with strong ground motions of nearby large earthquakes, and localized damages and flower-type structures around active faults based on previous studies of fault zone structures and recent 3D numerical simulations.

Chao and Peng (2009) examined temporal changes in seismic velocities and shear-wave anisotropy associated with the 10/22/1999, M6.4 Chia-Yi earthquake in Taiwan based on surface reflect waves recorded at a 200-m-deep borehole station CHY. We use the time delays between the up-going and down-going waves in the auto-correlation functions as the proxies for the two-way travel times in the top 200 m. The S-wave travel times measured in two horizontal components increase by ~1-2% at the time of Chia-Yi main shock, and followed by a logarithmic recovery, while the temporal changes of S-wave splitting and P-wave travel times are less than 1% and are not statistically significant. We obtain similar results by grouping earthquakes into clusters according to their locations and waveform similarities. This suggests that the observed temporal changes are not very sensitive to the seismic ray paths below CHY, but are mostly controlled by the variation of material properties in the top 200 m of the crust. We propose that strong ground motions of the Chia-Yi main shock cause transient openings of fluid-filled microcracks and increase the porosity in the near-surface layers, followed by logarithemic recovery processes. No clear change in the delay times of the shear wave anisotropy is found following the main shock, suggesting that cracks opened during the earthquake do not have a preferred orientation.

In the third study, we systematically analyzed temporal changes of fault zone (FZ) site response along the Karadere-D?zce branch of the North Anatolian fault that ruptured during the 1999 İzmit and D?zce earthquake sequences. We computed the spectral ratios of strong motion seismic data recorded by a FZ station and a station ~400 m away from the fault, and use them to track non-linear behavior and temporal changes of the FZ site response. The peak spectral ratio increases 80-150 per cent and the peak frequency drops 20-40 per cent at the time of

the D?zce main shock. These co-main shock changes are followed by a logarithmic recovery over an apparent time scale of ~1 day. However, analysis of temporal changes at each individual station using weak motion waveforms generated by repeating earthquakes show lower-amplitude longer-duration logarithmic recoveries that are not detected by the spectral ratio analysis. Our results are consistent with a reduction of S-wave velocities in the top 100-300 m during the D?zce main shock of 20-50 per cent or more, and logarithmic post-main shock recovery on a time scale of 3 months or more. The observations support previous suggestions that non-linear wave propagation effects and temporal changes of seismic properties are generated in the shallow material by strong ground motion of nearby major earthquakes.

We also performed a similar analysis of temporal changes in site response associated with the strong ground motion of the Mw6.6 2004 Mid-Niigata earthquake sequence in Japan. The seismic data is recorded at a site with accelerometers at the surface and the 100-m-deep borehole. We computed the empirical surface-to-borehole spectral ratios and use them to track temporal changes in the top 100 m of the crust. We observed that the peak spectral ratio decreases by 40-60% and the peak frequency drops by 30-70% immediately after large earthquakes. The coseismic changes are followed by apparent recoveries with the time scale ranging from several tens to more than one hundred of seconds. The coseismic peak frequency drop, peak spectral ratio drop, and the postseismic recovery time roughly scale with the input ground motions when the peak ground velocity is larger than ~5 cm/s (or the peak ground acceleration is larger than ~100 gal). Our results suggest that at a given site the input ground motion plays an important role in controlling both the coseismic change and postseismic recovery in site response.

Finally, Toteva et al. (2008) systematically investigate temporal changes in the near-surface layers and deep fault zone scatterers after the 2004 Mw6.0 Parkfield earthquake using many repeating aftershocks recorded by the USGS Parkfield Dense Seismograph Array (UPSAR). We found that the time delays and decorrelation index show significant variations within each station in the UPSAR for the same set of repeating clusters. We also found a positive correlation between the average time delays and the peak ground accelerations (PGA) recorded during the 2004 Parkfield mainshock. These results suggest that the observed temporal changes in the UPSAR are probably induced by the dynamic shaking of the Parkfield mainshock and mostly confined in the near-surface layers beneath each station. We suggest that variations in PGA and average time delays could be mainly caused by topographic effects, because they are the only obvious differences among these stations.

In summary, our findings on temporal changes in site response and fault zone properties are consistent with the inference of a widespread damage and nonlinearity in the near-surface layers associated with strong ground motions of nearby large earthquakes, and localized damages and flower-type structures around active faults. The shaking induced damages may offer an explanation for dynamic of triggering of earthquakes and generations of high-frequency extreme ground motions in the near surface layers. Our results suggest that systematic observations of temporal changes from repeating earthquakes not only provide additional evidence of widespread nonlinearity during strong ground motions, but also offer new insight into the long-term evolutions of FZ structures and interactions of earthquakes and faults.

Training and Development:

Two graduate students (Chunquan Wu, Peng Zhao) are supported by this project and one more (Kevin Chao) has been involved in the work. The publications formed the major components of the Ph.D. thesis work of students Wu and Zhao. In addition, one faculty (Toteva) and two undergraduate students (Gerasimenko, Bagchi) from Randolph College have been involved in the research. We trained both the graduate and undergraduate students with online tutorials for Seismic Analysis Code (SAC) and data management, basic Unix shell script languages, and Generic Mapping Tools (GMT).

Outreach Activities:

We have presented these works at several national conference meetings, such as American Geophysical Union annual meeting, and Seismological Society of America annual meeting. The PI Peng has given many department seminars on the topic of ?temporal changes and strong ground motion? in USC (February, 2007), CEE, GT (March 2008), China Earthquake Administration (June 2008), and Academia Sinica in Taiwan (March 2009).

Journal Publications

Zhao, P., and Z. Peng, "Velocity contrast along the Calaveras fault from analysis of fault zone head waves generated by repeating earthquakes", Geophys. Res. Lett., p. L01303, vol. 35, (2008). Published, 10.1029/2007GL031810

Wu, CQ; Peng, ZG; Ben-Zion, Y, "Non-linearity and temporal changes of fault zone site response associated with strong ground motion", GEOPHYSICAL JOURNAL INTERNATIONAL, p. 265, vol. 176, (2009). Published, 10.1111/j.1365-246X.2008.04005.

Wu, C.; Peng, Z.; Assimaki, D., "Temporal changes in site response associated with strong ground motion of 2004 Mw6.6 Mid-Niigata earthquake sequences in Japan", Bull. Seismol. Soc. Am., p. , vol. , (2009). Accepted,

Chao, K.; Peng, Z., "Temporal changes of shear wave velocity and anisotropy in the shallow crust induced by the 10/22/1999 M6.4 Chia-Yi, Taiwan, earthquake", Geophys. J. Int., p. , vol. , (2009). Accepted,

Zhao, P.; Peng, Z., "Depth extent of damage zones around the central Calaveras fault from waveform analysis of repeating earthquakes", Geophys. J. Int., p. , vol. , (2009). Accepted,

Books or Other One-time Publications

Chao, K. and Z. Peng, "Temporal changes of shear wave velocity and anisotropy in the shallow crust induced by the 10/22/1999 M6.4, and M6.0, Chia-Yi, Taiwan earthquakes", (2007). Conference abstracts, Published
Bibliography: Eos Trans. AGU, 88(52), Fall Meet. Suppl., Abstract T51C-0682

Chao, K. and Z. Peng, "Temporal changes of seismic velocity in the shallow crust induced by the 10/22/1999 M6.4, Chia-Yi, Taiwan earthquake", (2007). Conference abstracts, Published
Bibliography: Seism. Res. Lett., 78, 257

Wu, C., Z. Peng, and Y. Ben-Zion, "Temporal changes in fault zone site response caused by strong ground motion of the 1999 Mw7.1 Duzce, Turkey, earthquake", (2007). Conference abstracts, Published
Bibliography: Seism. Res. Lett., 78, 278

Zhao, P. and Z. Peng, "Depth extent of the damage and healing processes and velocity contrast along the Calaveras fault zone revealed from waveform analysis of repeating earthquakes", (2007). Conference abstracts, Published
Bibliography: Seism. Res. Lett., 78, 316

Peng, Z., and P. Zhao, "Early aftershocks of the 2004 Parkfield earthquake detected by a matched filter technique", (2008). Conference abstracts, Published
Bibliography: Seis. Res. Lett., 79(2), 303

Wu, C., "Temporal change of seismic velocity and site response for different scales and implications for nonlinearity", (2007). Thesis, Published
Bibliography: Master of Science Thesis, Earth and Atmospheric Sciences, Georgia Institute of Technology

Wu, C., Z. Peng, and Y. Ben-Zion, "Rapid temporal changes of fault zone site response associated with strong ground motion", (2007). Conference abstracts, Published
Bibliography: Eos Trans. AGU, 88(52), Fall Meet. Suppl., Abstract T51C-0681

Wu, C., Z. Peng, and D. Assimaki, "Systematic analysis of temporal changes in site response associated with strong ground motion in Japan", (2008). Conference Abstract, Published
Bibliography: Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract S51E-08

Toteva, T., Z. Peng, and P. Zhao, "Temporal changes in near-surface layers and deep fault zone scatterers after the 2004 Mw6.0 Parkfield earthquake observed by the UPSAR", (2008). Conference Abstract, Published
Bibliography: Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract S53A-1816

Zhao, P. and Z. Peng, "Identification of repeating earthquakes and spatio-temporal variations of fault zone properties around the Parkfield section of the San Andreas fault and the central Calaveras fault", (2008). Conference Abstract, Published
Bibliography: Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract S53A-1817

Gerasimenko, I., S. Bagchi, T. Toteva, and Z. Peng, "Looking for seismic scatterers: summer research experience for undergraduate students", (2008). Conference Abstract, Published
Bibliography: Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract ED51A-0549.

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

The obtained results so far suggest a wide-spread damage and healing processes inside active fault zones and in the top few hundred meters of the upper crust associated with the strong ground motion of nearby large earthquakes. Our results suggest that systematic observations of temporal changes from repeating earthquakes not only provide additional evidence of widespread nonlinearity during strong ground motions, but also offer new insight into the long-term evolutions of FZ structures and interactions of earthquakes and faults.

Contributions to Other Disciplines:

Our results of damage and healing processes inside active fault zones and in the near surface layers support that non-linear wave propagation effects and temporal changes of seismic properties are generated by strong ground motion of nearby major earthquakes. These results would create a broader impact within the field of geology, earthquake engineering, and rock mechanics on understanding of nonlinearity and strong ground motion, and rock damage and healing processes.

Contributions to Human Resource Development:

Two graduate students (Wu and Zhao) are supported by this project and one more (Chao) has been involved in the work. The publications formed the major components of the Ph.D. thesis work of students Wu and Zhao. In addition, One faculty (Toteva) and two undergraduate students (Gerasimenko, Bagchi) from Randolph College have been involved in the research.

Contributions to Resources for Research and Education:

I have created a Seismic Analysis Code (SAC) tutorial with some exercises online at http://geophysics.eas.gatech.edu/people/zpeng/Teaching/Sac_Tutorial_2006/. This tutorial has been used to train incoming Georgia Tech graduate students and summer interns on how to use SAC, as well as used by students at other institutions.

Contributions Beyond Science and Engineering:

Conference Proceedings

Categories for which nothing is reported:

Organizational Partners

Any Web/Internet Site

Any Product

Contributions: To Any Beyond Science and Engineering

Any Conference